Invited Paper

A proposed global atmospheric monitoring network based on standard stars

John T. McGraw*[a], Peter C. Zimmer[a], Steven W. Brown[b], Gerald T. Fraser[b] Keith R. Lykke[b], Allan W. Smith[b], Christopher W. Stubbs[c], John T. Woodward[b],
[a]Dept. of Physics and Astronomy, Univ. of New Mexico, Albuquerque, NM 87131;
[b]National Institute of Standards and Technology, Physics Laboratory, Gaithersburg, MD 20899;
[c]Dept. of Physics, Harvard University, Cambridge, MA 01451

ABSTRACT

The feasibility of developing a network of telescopes to monitor the composition of the nighttime atmosphere using stellar spectrophotometry is explored. Spectral measurements of the extinction of starlight by the atmosphere would allow, for instance, quantification of aerosol, cloud, water-vapor, and ozone levels over the full range of elevation and azimuth. These measurements, when combined with data from solar spectrophotometry derived from other instruments, would provide continuous day/night monitoring of the atmospheric composition from the ground. The foundation for such an effort would be a set of stable standard stars with known top-of-the-atmosphere spectral irradiances traceable to international standards based on the SI system of units. Fully automated, reliable, easily maintained and highly cost-effective replicas of the spectrophotometric telescope used to calibrate the standard stars can be deployed worldwide at sites such as atmospheric and astronomical observatories.
Keywords: climate change, standard stars, spectrophotometry, stellar calibration

1. CLIMATE CHANGE: THE IMPORTANCE OF MEASURING AND UNDERSTANDING EARTH'S ATMOSPHERE

Synoptic climate change drives significant economic, civil and societal change. Scientifically determined to be an anthropogenic effect with largely negative outcomes, measurement of the physical parameters, the time-rates-of change, and the uncertainties for the physical mechanisms driving climate change is potentially the most socially significant scientific endeavor of the current century.

Response to climate change is clearly of critical importance, and by using nighttime observations of stars we propose to address two of the most uncertain of the parameters driving climate change: the vertical transmission of the atmosphere from 320 nm to 1050 nm, and the effect of aerosols on that transmission and on radiative forcing.

The scientific case and data sources are compiled by the United Nations- and World Meteorological Organization-sponsored International Panel on Climate Change. The IPCC publications provide a scientifically reviewed assessment of climate change and the status of the measurements that provide the critical data from which climate change is deduced. The greatest impetus for climate change research is provided by the IPCC statements:

- "*Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice and rising global average sea level.*" (IPCC 2007).
- *"Observational evidence from all continents and most oceans shows that many natural systems are being affected by regional climate changes, particularly temperature increases."* (IPCC 2007).

Our work responds to this impetus and takes further direction from the IPCC, including the necessity to reduce uncertainties in the measurements and parameterizations of climate change leading to policy input (IPCC 2007, 2009).

*jmcgraw@as.unm.edu; phone 1 505 277-2705; fax 1 505 277-1520

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We can extract and list the vital issues concerning scientific measurement of climate change parameters from the IPCC reports. These are:

- Measurement techniques that provide *accurate* data on all the relevant parameters involved with climate, climate modeling, and ultimately climate change are required.
- The measurements must have *documented uncertainties* that are sufficiently small that trends in parameter measurements are unambiguous.
- The instruments used must be *calibrated to physical standards* for long-term (*e.g.* decade and century) use, thus ensuring that data sets remain valid long after the instruments that have made them are replaced.
- The suite of instruments must be *replicable and capable of long-term use in the field* with minimal support, thus enabling global observations of the same parameters.

We describe a replicable ground-based spectrophotometer that fulfills these criteria and is capable of accurately establishing and *maintaining* incontrovertible nighttime *measurements* that define values and trends amongst parameters that vitally bear on long-term climate change. Replicated spectrophotometers, distributed world-wide at atmospheric and astronomical observatories, observe a set of stars calibrated as accurate sources – *SI Stars*. Longevity of the sources and instrumental technique is critical because, even if humans respond positively to suggested climate change mitigation efforts, accurate monitoring as we propose will be necessary into the future to demonstrate that these efforts are working to the degree predicted.

Because of the importance of atmospheric monitoring, we propose a system of standard stars that provides an external, nearly eternal (on human time scales), basis for calibrating both ground- and space-based sensors. A particular application for SI Stars involves the expensive fleet of spacecraft that currently and into the future monitors the atmosphere and makes measurements to decipher climate change. Over years these instruments must produce highly accurate measurements to fulfill their missions. The accuracy requirements and the commensurate measurement uncertainties are rarely provably met. Stars, however, are always accessible and, if we do our job well, will provide radiometric calibrators and validation references stable over time scales longer than the time scale of climate change.

2. SI STARS – A THOUSAND POINTS OF WELL-CALIBRATED LIGHT

Stars, conveniently placed point sources of light distributed across the nighttime sky, shine for a long time. Our sun has shone for about five billion years, and will last for about another five billion years before entering a rapid phase of evolution during which it turns into a red giant star and expands nearly to include Earth's orbit – at which point the need for radiometric standards largely evaporates. Theoretically and conceptually, stars should be exquisite radiometric standards for terrestrial and space-based instruments and sensors: they are well-known thermal sources that radiate from the ultraviolet to the infrared; the radiation from the star can be accurately understood, predicted, interpolated and extrapolated with stellar model atmospheres; stars appear to be radiometrically stable over exceedingly long periods of time; there are enough stars that are sufficiently bright to be candidate standard stars that they are reasonably evenly distributed across the entire celestial sphere; the members of this set of calibrated standard stars are bright enough to be measured with small to moderate telescopes. Additionally, when considered from the perspective of climate change monitoring, every star illuminates an independent path through the atmosphere, and atmospheric transmission can be mapped across the nighttime sky by continuously observing standard stars with an inexpensive, distributed suite of small telescopes. The entire range of altitude and azimuth is accessible and can be reasonably sampled in the time domain. Clearly, a dense network of calibrated standard stars provides an ideal technique for precisely and accurately measuring the transmission of Earth's atmosphere at night. Long-lived standard stars will provide accurate calibration of climate change measurements into the next decades and centuries with known small uncertainties that make unambiguous detection and interpretation of anthropogenic climate change more certain.

The benefits of a standard star system, calibrated in SI units and with known flux measurement uncertainties, extend beyond ground-based climate change measurement and monitoring. This set of stars will be continuously accessible for calibration of space-based instrumentation. This implies broad civil, commercial, scientific and military applications for these stars. Space-based detectors, and their calibrators, are known to age significantly on-orbit. A network of standard stars will allow on-orbit re-calibration. Also, extended to fainter stars, this standard system will establish the

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measurement accuracy required by the astronomy and astrophysics communities to better address research topics, including investigating the nature of dark matter and dark energy both from space and from the ground.

Unfortunately, creating a standard star network is more difficult than is usually imagined. Stars come in a variety of physical configurations and, because we live in the disk-like Milky Way Galaxy, are anisotropically distributed on the sky, which leads to potential problems in identifying candidate standard stars. In particular, some stars are born in binary and multiple stellar systems. They thus radiate composite spectra weighted by the luminosity of each component. This is an extrinsic effect that must be evaluated to decide if a star is worth calibrating. Some stars, especially luminous evolved stars, are luminosity variable, thus precluding their use as standard stars. This is an intrinsic effect which also must be evaluated. Other stars are optical doubles (*i.e.* in the same line of sight but not physically related) or occur in crowded regions of the Milky Way. These are angular proximity or field effects. Occasionally the background for a potential standard is affected by the seeing-blurred point spread function (PSF) of some nearby bright star – another field effect. The most luminous stars will be seen at great distance and will thus appear redder and fainter than they really are because of absorption and scattering by interstellar dust. Because dust is most concentrated in the plane of the Milky Way, this is again an effect correlated with the field of the candidate star. Standard star candidates must, therefore, be carefully vetted before expending the resources to attempt calibration and long-term monitoring.

Thus, "spectrophotometric standard star" requires definition. The ambitious goal we set is to produce 0.5 % absolute spectrophotometric flux measurements in SI units from 300 nm to 3.5 µm. This calibration will ultimately be extended past 10µm into the thermal infrared driven by atmospheric radiative transfer and climate change modeling. The first steps we discuss here involve demonstrating the required level of accuracy for the spectral region 320 nm to 1,050 nm where relatively inexpensive, well-known and characterized CCD detectors are sensitive. The definition derives from both IPCC requirement for measuring radiative effects in Earth's atmosphere and from requirements for precision measurements for investigating the nature of dark energy and dark matter by the astrophysics community.

3. HOW TO MAKE A STANDARD STAR

Establishing new fundamental flux standard stars requires four steps:

1. Define a catalog of candidate spectrophotometric standard stars.
2. Implement absolute throughput and wavelength calibration of the calibrating spectrophotometer.
3. Upgrade real-time capability to correct for atmospheric extinction with better than 1 % accuracy.
4. Rigorously and repeatedly observe candidate standard stars from approximately 320 nm to 1050 nm with regularly determined NIST-calibrated throughput, modeling the stellar spectrum as an invariant source function (*e.g* Sordo *et al.* 2009) and the Earth's atmosphere as a time-, direction- and wavelength variable turbid medium (MODTRAN, Berk *et al.* 2005) with transparency corrections calculated at one minute cadence.

3.1 Flux Calibration – Prior Art

Fundamentally, calibrating a star is simple: one measures a stellar spectrum and the spectrum of a radiometrically-calibrated source over the same spectral bandpass and the ratio of the stellar spectrum to the spectrum of the standard source provides the calibrated stellar spectrum. Unfortunately, this is a real-world measurement that involves measurements made through Earth's ever-changing atmosphere, and is nowhere near this simple.

Astronomers, often employing literally heroic efforts, have determined the flux calibration of stars relative to laboratory standards (Code 1960 and references therein, Hayes 1970, Oke and Schild 1970, Hayes, Latham and Hayes 1975, Hayes and Latham 1975) expressed in spectral irradiance units of ergs s^{-1} cm^{-2} Hz^{-1}. These calibrations, based upon blackbody radiation from gold, copper or platinum at their freezing temperatures, ultimately defined Vega as the primary spectrophotometric standard in the sky. The calibration sources were burdened by issues such as the accurate measurement of temperature, and melting point variations resulting from contamination – and these uncertainties create flux uncertainties as ΔT^4. This calibration, however, ultimately enabled and supported certainly hundreds and probably thousands of Galactic and extragalactic research efforts, principally by providing the primary standard, Vega, that allowed differential observations to define secondary (and tertiary) spectrophotometric standard stars for ground- and space-based observations.

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All of the classical flux calibration literature addresses the importance of atmospheric transmission (extinction corrections) as a primary source of systematic error in flux calibration (*e.g.* Hayes and Latham 1975). The fundamental calibrations were carried out by observing stars through some airmass, for which classical nightly mean extinction was determined. Those observations were interspersed with observations of blackbody sources with the telescope horizontal. Atmospheric extinction was corrected on the basis of a plane-parallel atmosphere at the altitude of the observatory. Both of these extinction corrections are the consensus source of systematic error. We concur and assess the effects when we discuss the evil atmosphere in Section 3.5, below.

The quoted calibration uncertainty of these classical measurements is typically 1 or 2 percent, though wavelength-dependent systematic errors of up to 5 % are obvious in spectrophotometric comparisons of Vega acquired by different groups, often using different measurement techniques and radiance standards. Megessier (1995) analyzed the accuracy of astrophysical flux calibrations in terms of f_{5556} for eight calibrations and concluded that discrepancies amongst determinations can be ~ 4 %. Megessier also concluded that extension of calibration into the near infrared was uncertain because Vega produced more near infrared flux than any direct calibration or f_{5556} –calibrated model predicted. This is consistent with the interpretation that Vega supports a debris disk that perturbs the stellar infrared flux (Selby *et al.* 1983, Blackwell *et al.* 1983). The final driver to establish new spectrophotometric standard stars was provided by Peterson *et al*. (2006) who determined that Vega, the community's shining star of calibration hope is, in fact, a pole-on rapid rotator, making flux distribution modeling, especially into the near-infrared, less certain than is probably reasonable for the astrophysics community's primary stellar flux standard. These perturbations to the Vega spectrum were largely discovered *because* Vega is the primary spectrophotometric standard, and underlines the necessity for care in selecting new standards.

3.2 Selecting Spectrophotometric Standard Stars

The prelude to calibrating spectrophotometric standards is thus to identify stars that, to all appearances, are single, stable stars with no field contamination, at least to the spectrophotometric accuracy limits set by our definition. The input catalog for this task is the HIPPARCOS catalog (van Leeuwen 2007), which lists fundamental measurements for reasonably bright stars, including their positions in equatorial coordinates, apparent magnitude in the visual (V) bandpass centered at about 550 nm, B-V color, variable star type (if a known variable), and the spectral type. For the purposes of creating the "cleanest" possible list of potential spectrophotometric standard stars from northern hemisphere observations, based upon valid but arcane astrophysical reasons, we eliminate:

- Stars south of declination -30º (though southern stars will be added at a later date)
- Stars fainter than V of 5.5 magnitudes
- All known variable stars
- Double and multiple star systems
- Stars with emission line spectra
- Stars with peculiar spectra
- Spectroscopic binaries
- Pre-main sequence stars
- Stars with spectral type later than K
- Flare stars
- Novae
- Stars identified with nebulosity

This results in a catalog of 807 *candidate* spectrophotometric standard stars reasonably distributed on the sky, as shown in Figure 1, that are targets for the Astronomical Extinction Spectrophotometer (AESoP).

3.3 Design of a True Spectrophotometer

The primary goal of spectrophotometry is to keep track of all the photons entering the well-defined aperture of the telescope. Classical spectrometers typically include the fore-optics of the telescope (most often the primary and secondary of a Cassegrain telescope), a slit, collimator, grating, camera and detector. After considering options, we concluded that the simplest possible spectrometer results in the most accurate spectrophotometry. We therefore designed

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AESoP as an objective grating refracting telescope (e.g. Hale and Wadsworth 1896). Our objective grating spectrometer provides the decided advantage that there are no color-dependent optics, slits, fibers or cameras (except for an order-separating filter) beyond the objective. All of the light entering the objective ends up on the detector, and if all of the light entering the objective can be accounted for on the detector, the system is spectrophotometric. There are, of course, drawbacks to the objective spectrometer, including the fact that the seeing and telescope tracking affect the spectral resolution, but AESoP was designed to minimize these effects.

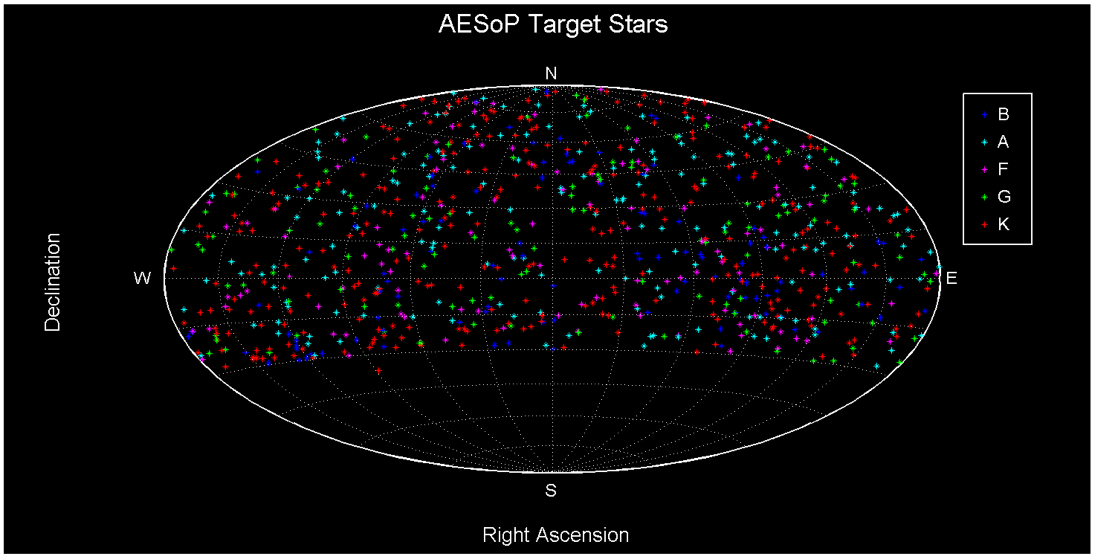

Figure 1. Distribution of AESoP Target Stars with $V \leq 5.5$ on the dome of the sky. Stars are color encoded from the hottest, bluest B-type stars to the coolest, reddest K-type stars.

This simple spectrophotometer has several very positive benefits for this project. The most significant is that once light enters the telescope there are no other light losses or chromatic effects. The photometric accuracy of AESoP is determined by 1) the calibration of telescope throughput, 2) the area of the aperture, and 3) extraction, reduction and analysis of the spectrum imaged onto the CCD. Other benefits include small aperture size, low cost, ease of replication, and portability. Additionally, night sky emission lines, which radiate from every point on the sky, become part of the diffuse background light and do not add line contamination to the stellar spectrum. If necessary, the grating can be rotated to orient a standard star spectrum so that it is uncontaminated by spectra of other stars in the field of view. The instrument has very high throughput from 320 nm (ozone opacity limit) to 1,050 nm (silicon detector sensitivity limit). Sequential selection of one of two order separation filters just in front of the CCD allows obtaining second-order spectra from 320 nm to 550 nm and first-order spectra from 550nm to 1050nm. AESoP is small enough that it can be calibrated by observing a monochromatically-illuminated flat-field screen, by collimated light projection techniques, or both. AESoP is shown in its dome in Figure 2.

Characteristics of AESoP:

- Built on a 106 mm f/5 Takahashi 106Q apochromatic refractor
- Equatorially operated on Parallax HD150C mount
- Newport Optics 102 mm square 90 line/mm transmission grating blazed at 700 nm in 1st order mounted at the entrance aperture
- Filter wheel with selection of order separating filters and narrowband wavelength calibration filters
- Thermoelectrically cooled, back-illuminated 2048 x 512 E2V 42-10 CCD detector yielding 5.3 arcsec/pixel in spatial direction and 0.28 nm/pixel in dispersion direction
- Free spectral range 320 nm to 1050 nm
    - 320 nm to 550 nm with shortpass filter

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    - 550 nm to 1050 nm with longpass filter
- Two pixel spectral resolution 0.57 nm, R=1140 at 650 nm
- Seeing ≤ 3 arcsecond (FWHM), *i.e.* smaller than one pixel
- Autoguiding to ~ 0.3 arcsecond resolution
- S/N > 100 per pixel achieved by controlling instrumental and background noise and observing bright stars

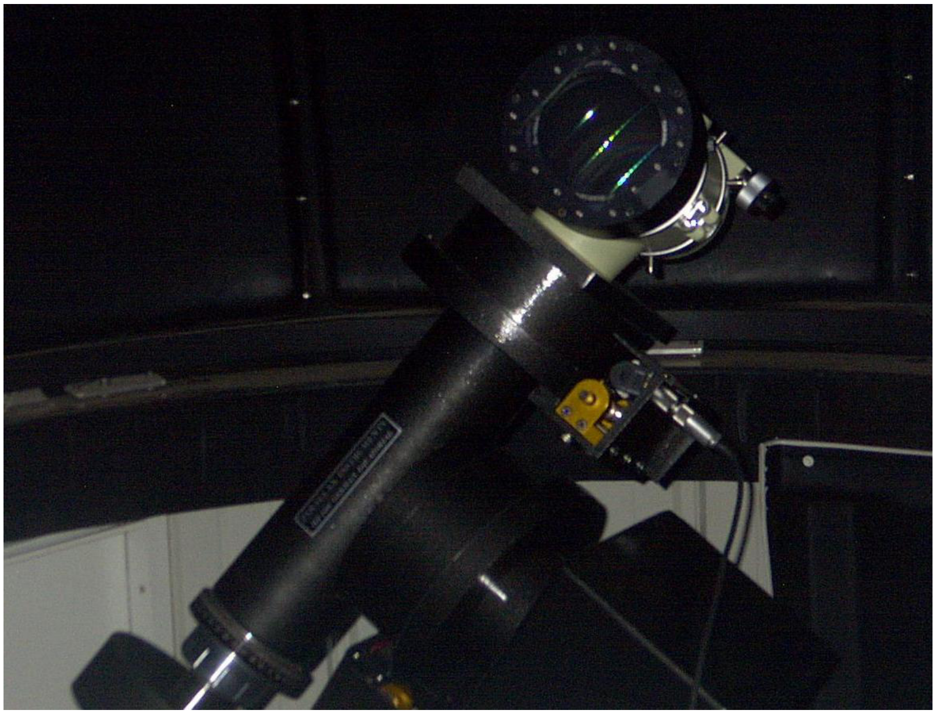

Figure 2. The Astronomical Extinction Spectrophotometer (AESoP). The transmission grating can be seen in its black mounting cell at the aperture of the 105mm refractor. AESoP is equatorially mounted to ensure that the spectrum remains on the same pixels for the duration of each exposure.

An AESoP spectrum of Vega acquired as 10 one-second exposures, resulting in signal-to-noise greater than 200 per pixel, is shown in Figure 3. The O_2 and H_2O transmission functions that affect this spectral region modeled by MODTRAN are shown for nominal Albuquerque pressure and 20 mm of precipitable water vapor.

3.4 Throughput and Wavelength Calibration

NIST has developed emitter and detector flux standards that are both more accurate and far easier to reference than the blackbody standards previously used in astronomy. Driven both by scientific need and by technological opportunity, we propose to establish SI Stars as a new generation of spectrophotometric flux standard stars. The principal goal of this project is to implement primary flux standard stars for use in the climate change and astrophysical communities by calibrating new spectrophotometric observations using NIST-calibrated photodiodes as flux standards. We further propose to correct accurately for atmospheric extinction, the recognized largest source of systematic error, by using simultaneous real-time, direct measurements of Earth's atmosphere. The result will be NIST-traceable flux standards in the northern sky.

The two largest challenges for AESoP are wavelength calibration and wavelength-dependent absolute throughput calibration. Because there is no slit in this system, variations in telescope pointing are confused with the wavelength calibration (*i.e.* what pixel position corresponds to what wavelength). In addition, system sensitivity is a function of field position due to field dependent throughput and pixel-to-pixel variations in the quantum efficiency of the CCD. We propose to solve these issues straightforwardly.

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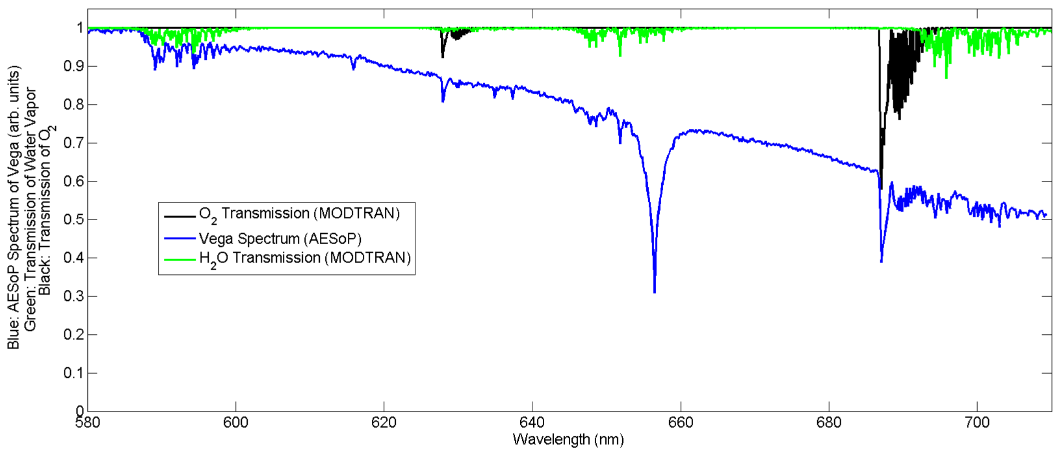

Figure 3. Normalized AESoP spectrum of Vega at Hα with 0.15 nm pixel resolution and S/N > 200 at 670 nm resulting from 10 one-second integrations. MODTRAN modeled atmospheric O_2 for ABQ nominal pressure and H_2O for 20 mm PWV are shown. AESoP is capable of providing spectra for fundamental laboratory calibration for stars to V $\leq$ 5.5.

AESoP is made an absolute spectrophotometer by mounting two 50 mm telescopes that have been previously calibrated at the NIST Telescope Calibration Facility (TCF: Smith *et al*. 2009) on either side of the primary aperture but within the collimated output beam of the calibrator. Two calibration telescopes allow for a cross check and also account for overall illumination gradients (gradients within the aperture of AESoP will be tested for and corrected by use of specially designed aperture masks). The use of ancillary telescopes is advantageous because they can be easily swapped out and recalibrated and because they will only be used for calibration, they can be protected from dust accumulation that is typical at most astronomical sites during sky observations. With the addition of calibration telescopes sampling plane-parallel light essentially at the entrance pupil, any wavelength that AESoP sees can be quantified in physical units (watts per square meter). Thus, AESoP must be calibrated wavelength-by-wavelength in a simple and repeatable way, but once done, any object appropriately observed will have a NIST traceable flux.

Because there is no place where calibration light can be injected into AESoP aside from the primary aperture, calibration lamps normally used in astronomical spectrometers cannot be used. Stubbs and Tonry (2006) addressed absolute calibration of telescope throughput based upon a luminous flat-field screen. For AESoP, calibration sources must be collimated light injected at the primary optic, and in order to maintain spectrophotometric integrity, they must fill the entire aperture. There are two ways of filling a telescope aperture with collimated light, collimate the source with optics of the same size or larger or move the source a long distance away, each has advantages and drawbacks. We propose two techniques for establishing and maintaining absolute throughput calibration, using a distant source must account for atmospheric extinction to the calibrating source. Using a close, collimated source requires careful control over illumination uniformity. Both techniques are purposely proposed as cross-checks on the calibration of these high-value observations.

For calibration using a distant source, NIST has developed radiometric techniques using stable, uniform sources and stable detectors that form the basis of the Spectral Irradiance and Radiance Responsivity Calibrations using Uniform Sources Facility (SIRCUS: Brown *et al*. 2004). For the specific purposes of repeatedly calibrating AESoP (and other spectrophotometric telescopes), a simple derivative of SIRCUS has been developed. A wavelength selectable, point-like source can be placed approximately one kilometer from the telescope and used as a flux standard for absolute throughput calibration. The distant source requires correction for absorption and scattering by the atmosphere, which is provided by an ancillary telescope, calibrated at the TCF, mounted on AESoP.

For the *in situ* calibration, AESoP will be pointed at a collimating telescope, the output aperture of which overfills both AESoP's aperture and the calibration telescopes as well. The collimating telescope is fed by a fiber, baffled to appear as

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a point source in its focal plane, which is illuminated by a monochromator. The output of the collimator will appear as a distant point source to AESoP that can be stepped through wavelength, transferring the calibration established on the calibrator telescopes to AESoP.

Wavelength scale and wavelength sensitivity calibrations are coupled with AESoP. Therefore, it is essential that the telescope put the same wavelength on the same pixel every time and keep it there. This will be accomplished by always placing the image at 532 nm (doubled YAG), for the blue second order spectral range, and at 632.8 nm (HeNe), for the first order red spectral range, in the same place on the detector both in calibration images and science object images, as discussed below.

For the calibration process, AESoP will first observe the calibrator which will transmit laser light, either 532 nm or 632.8nm. AESoP will make an image of the fiber tip that is in the calibrator telescope focal plane and it will place that image in the same pixel for every calibration and stellar image. Once the HeNe source position is fixed, the calibrator can cycle through calibration sources, the most important of which is the light from the monochromator. The filter wheel in front of AESoP's CCD contains a variety of blue blocking filters, but will also carry special narrowband HeNe and doubled YAG filters manufactured to operate in the f/5 converging light of AESoP. With this filter in place, the monochromator can first be tuned to 632.8 nm to verify that the wavelengths of the monochromator match the HeNe calibrator. Then the filter can be moved out of the way and a blue blocker filter moved into position. AESoP then acquires accurately timed exposures controlled by a precision double-bladed shutter as the monochromator steps through wavelength.

The product is a combined wavelength calibration and flux calibration. To transfer the wavelength solution onto the sky, the 632.8 nm filter is put in place and the image of the target star is centered so that the 632.8 nm stellar image is in the same spot as the 632.8 nm monochromator image from the calibration process. This assures that the wavelength-to-pixel mapping is the same as for the calibration data frames. The acquired stellar spectrum is now calibrated in absolute flux and wavelength units. The process is identical for the red spectrum using the 532 nm doubled YAG source.

3.5 Earth's Evil Atmosphere: The Limiting Factor to Fundamental Uncertainties

Because scattering and absorption in Earth's atmosphere is the principal source of systematic error in spectrophotometry, the absolute transmission through the atmosphere must be measured:

a. Over the optical path length to a remote calibration source, and
b. Continuously as standard star observations are made.

For this purpose we developed the Astronomical Lidar for Extinction (ALE), which provides monochromatic absolute transmission of Earth's atmosphere at 527 nm. Spectra obtained with AESoP are "pinned" at this wavelength, ultimately resulting in an extinction-corrected standard star. Once calibrated to the defined accuracy, the standard star spectrum becomes a source function for deriving the physical and chemical structure of the atmosphere.

Other than supporting life, Earth's atmosphere is evil – it is a primary source of systematic measurement errors in ground-based observational astrophysics, and these sources of systematic errors are often unrecognized. They are, however, critical to the establishment of fundamental stellar flux standards. The systematic photometric errors introduced by observing through the atmosphere are well described and analyzed by Stubbs *et al.* (2007).

For decades astronomers have corrected for astronomical extinction with insufficient fidelity; for example, using nightly derived mean atmospheric extinction solutions, while the atmosphere changes on time scales of a minute and angular scales smaller than a degree, introduces often unrecognized and previously always unknown systematic error. This is demonstrated in Figure 4.

Atmospheric extinction always has a well-defined mean – but often with large variance. Figure 4 demonstrates that significant transparency variations occur on minute timescales and that the error induced by changing transparency for a typical 15 minute exposure can easily be larger than a single measurement error. Most significantly, a nightly mean extinction coefficient, represented by the solid black line, with standard deviation of 1.4% determined from measurements made throughout the night, insufficiently represents the true extinction at the beginning and end of the night, ensuring a ~ 1% extinction correction error in each case. While this night demonstrates a monotonic trend in

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decreasing extinction, this total fluctuation amplitude for a clear night is not uncommon. This is the canonical night spent observing only to discover that the acquired data quality is worse than expected – and perhaps unusable – because of systematic errors introduced by not adequately measuring extinction variations. It is precisely this case that the Astronomical Lidar for Extinction (ALE) was designed and built to address.

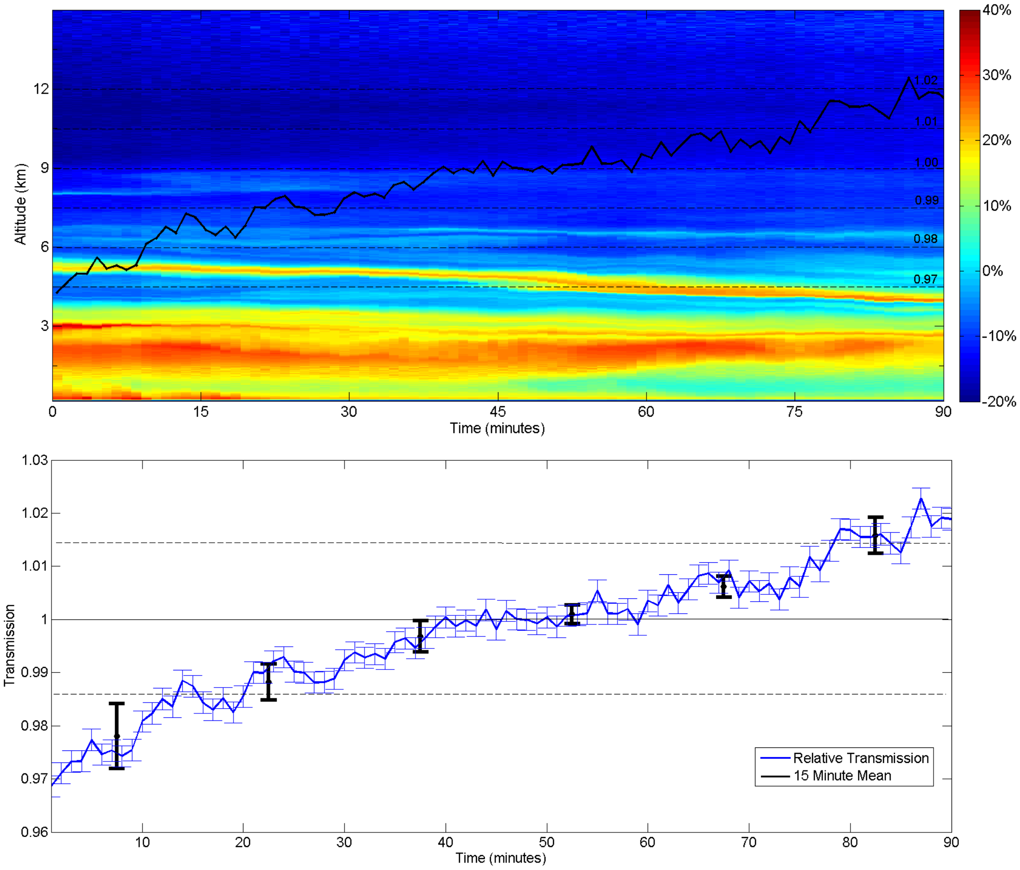

Figure 4. The upper panel shows an Astronomical Lidar for Extinction (ALE) zenith time-height diagram for 18 April 2008 acquired by averaging lidar returns in one minute of time bins over an interval of 1.5 hours. The returns, expressed as the fractional difference (data – model)/model, where the model is a standard atmosphere plus an exponential aerosol. The black trace shows the relative transmission which is replicated in the lower panel with one minute, 0.2% single measurement standard deviations shown. Fifteen minute means with the standard deviation of the mean are shown with black error bars. These data derive from a clear night that would have been used for astronomy. Transparency changes are due to changing aerosol distributions.

Inferring extinction for any single image or observation by observing stars through the atmosphere is clearly insufficiently precise to obviate the systematic effect of extinction changing on multiple time and angular scales, even with a simultaneously operating ancillary "calibration" telescope. Precise correction for extinction requires direct, precise, time- and range-resolved observation of Earth's atmosphere.

3.5.1 The Astronomical Lidar for Extinction (ALE)

ALE, shown in Figure 5, is an eye-safe single wavelength (527 nm) elastic backscatter LIDAR built by UNM in collaboration with Georgia Tech Research Institute (Dawsey *et al.* 2006) and installed at the UNM Campus Observatory. LIDAR (Light Detection And Ranging) is the laser analog of radar. ALE transmits a 24 ns long, 305 mm diameter laser pulse 1500 times per second from its transmitter. Each pulse, as it passes through the atmosphere, is scattered and absorbed by the intervening atmospheric constituents. At a given altitude, some fraction of the scattered light will be scattered back into the direction from whence it came. That backscattered light then is scattered and absorbed again by the same material it passed through on its outward path, until it returns to ALE's receivers. Those photons are collected

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by the 100 mm diameter short range receiver and the 670 mm diameter long range receiver. Each receiver is a telescope that focuses the return onto a time-gated photomultiplier tube. The recorded signal at a given altitude is directly related to the density of scatterers and the intervening transmission.

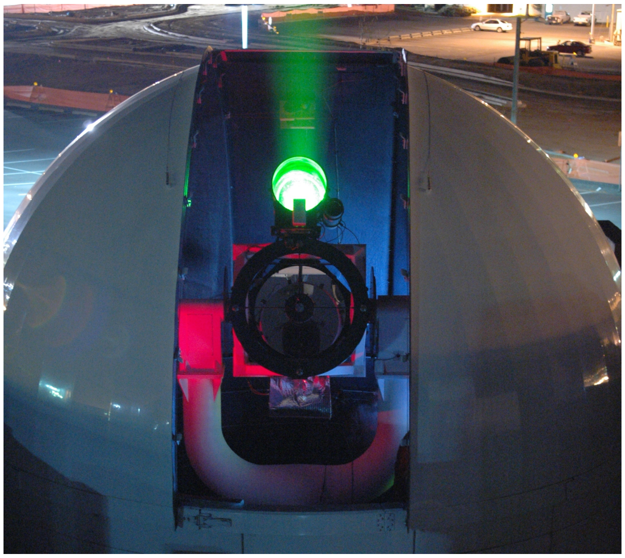

Figure 5. Looking down ALE's alt-az mounted 670mm diameter long-range receiver. The green illuminated tube above the long-range receiver is the 330mm co-mounted laser transmitter, which is flanked on the right by the 100mm short-range receiver (photo by David Roberts).

Rayleigh scattering is rather better behaved than the other atmospheric opacity effects. By operating at 527 nm, ALE avoids a number of detrimental absorption effects and its signal is only sensitive to Rayleigh scattering, a small amount of ozone absorption (~1.5 %), aerosol scattering and absorption, and scattering by clouds. Above the tropopause (~12 km), aerosols are rare and clouds are essentially non-existent. The Rayleigh scattering component above the tropopause is thus far more slowly varying and trends with the surface pressure. The ozone content is more problematic in that it varies, though those variations create only small corrections to the nominal ozone absorption. Moreover, the column and profile of ozone is measured by satellite. This means that the molecular scattering component sufficiently high into the stratosphere can act as a quasi-constant scattering target and allows calibration of the total transmission to that altitude. The remainder of the transmission from above this region (a few percent) is sufficiently stable that, once calibrated, will not change more than 0.1 % over periods of weeks.

Relative transmission can be measured under any conditions just by looking at the return from a pre-determined altitude range above the tropopause as a function of time. At these altitudes, the return is strongly dominated by molecular scattering and changes slowly with time and proportionally to surface pressure. Therefore observed variations are due to variable transmission below the target altitude. Varying transmitted laser power can be confused with transmission variation, thus ALE measures the transmitted laser power before the beam expansion stage to 0.05 % for each one minute profile.

Figure 6 shows the fractional return with respect to a fiducial model as a function of time and altitude – a dust layer settles between one and four kilometers and several cirrus layers are present between six and nine kilometers. Analyses such as these are able to discern variations of less than 1 % in backscatter density up to 25 km above sea level.

3.5.2 The Atmosphere Observed by Astronomers

Earth's atmosphere contains multiple absorption and scattering mechanisms, most of which play crucial roles in radiative transfer through and within the atmosphere. Some of the relevant constituents, such as Rayleigh scattering and stratospheric ozone column density, change slowly over a night and over the dome of the sky, while others, specifically

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water vapor, clouds and aerosols, change rapidly, on timescales of minutes and angles smaller than an arcminute. These considerations ultimately drive the requirements for astronomers to monitor Earth's atmosphere while observing. *The astronomical considerations required to correct for extinction of starlight are identical to those addressed when monitoring atmospheric transparency.*

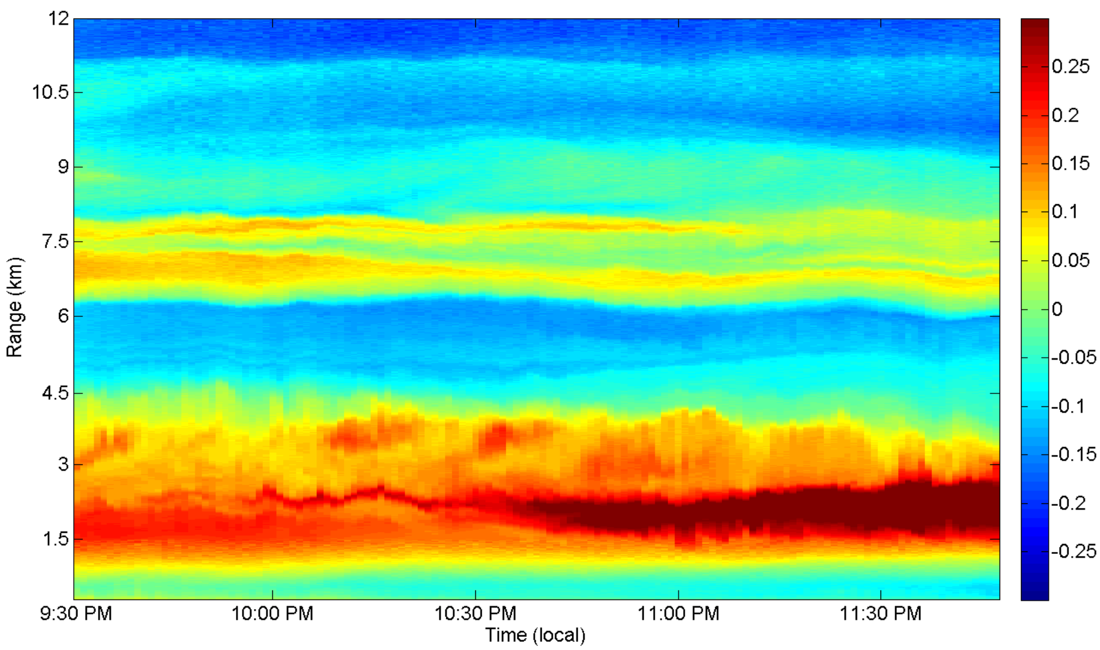

Figure 6. A time-height diagram from 10 June 2008 that shows the return signal versus time and range for a series of vertical scans of the troposphere above ALE. The return is measured with respect to a fiducial modeled return such that the color scale values are the fraction of the return above or below the model value.

The dominant effects of atmospheric turbidity in wavelength region from 320 nm to 1050 nm can be categorized as caused by four broad physical effects, each with its own distinct temporal, angular and spectral signature: scattering from molecules, absorption by molecules, scattering and absorption by aerosols, and scattering by clouds. Absorption and scattering are depicted in Figure 7. There are a number of other effects as well, but we limit this discussion to those that play a role at the ~ 0.1 % level or greater in terms of their spectrophotometric impact. We describe each effect together with the specifics of the dominant molecular species.

- Molecular Scattering: The most stable component of the atmosphere in terms of its effect on transport of radiation is molecular, or Rayleigh scattering. This occurs when a photon elastically scatters from particles much smaller than its wavelength (molecules) along its nominal trajectory. Rayleigh scattering is very well understood and modeled (Bucholtz 1995; Tomasi *et al.* 2005). Because Rayleigh scattering is directly proportional to the number of scatterers along the propagation path, the overall magnitude of the effect scales with surface pressure (Hansen & Travis 1974).
- Molecular Absorption: Three molecular species, O_2, O_3 and H_20 contribute most to molecular absorption in the 300nm-1100nm band. Absorption bands of O_2 occur at 760 nm, 690 nm, 630 nm and 580 nm but are very stable. Ozone has a broad absorption feature (the Chappuis band) between 450 nm and 850 nm with a maximum transmission loss of ~3.8 % at 602 nm (Burrows *et al.* 1999). Ozone also absorbs blueward of 350 nm, increasing with shorter wavelength until the atmosphere is essentially opaque at wavelengths shorter than 300 nm. The absorption from the Chappuis band scales linearly with the column density of ozone along the line of sight of an observation. Ozone exhibits a broad spectrum of temporal variation with annual fluctuations between 5.9 - 9.5 x 10^{18} molecules/cm^2 and with daily variations of ~5 %, though these can be as high as 15 %. Water vapor is by far the most problematic of the molecular species that absorb in the visible spectrum, with many large and variable bands including prominent ones at 940 nm, 820 nm and 720 nm and many smaller ones

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blueward to 440 nm. Water vapor is also highly time and spatially variable and the various lines within the deeper bands are saturated. Lastly we lump NO_2, SO_2 and a few other species together as trace gasses. Under typical conditions, these gasses contribute to transmission loss of less than ~1 % in many different bands throughout the optical and NIR.

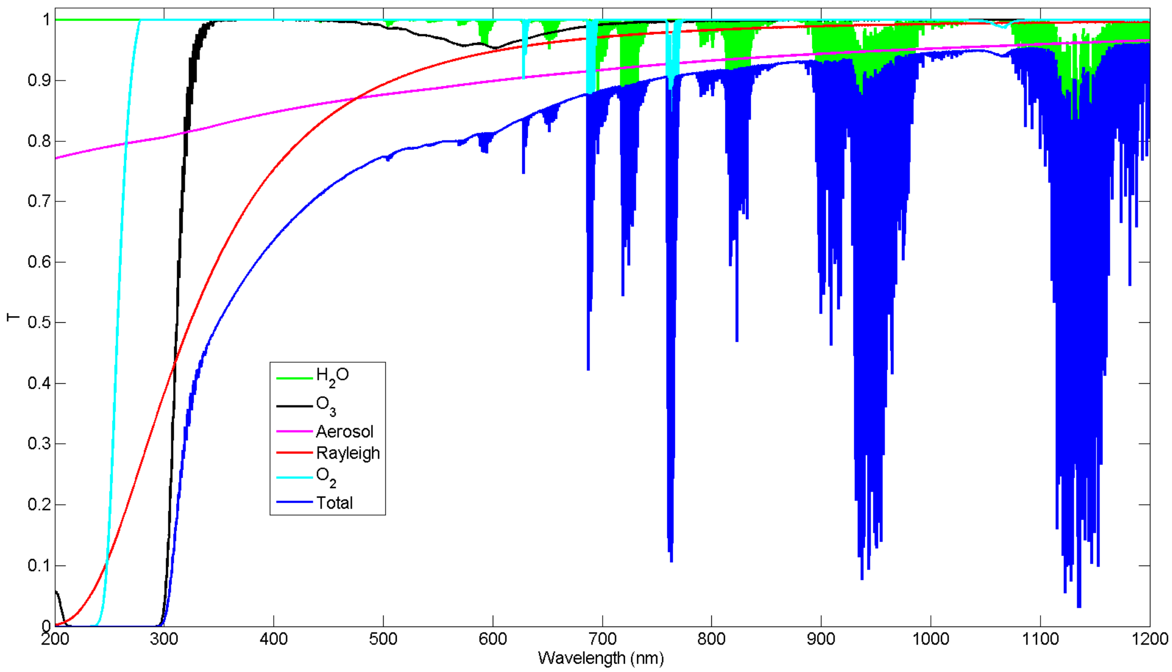

Figure 7: MODTRAN (Berk *et al*. 2005) model of nighttime zenith atmospheric transmission showing contribution by mechanism. Parameters of the model were chosen to be similar to those expected for a high-altitude desert observatory site.

- Aerosol Absorption and Scattering: Aerosols comprise a broad category of particulate matter aloft in the atmosphere, including dust, smoke, soot, pollen and sea salts (*e.g.* Prather *et al.* 2008). The unifying property of these constituents is their size, ranging from 0.1 microns up to 10 microns, placing them in the size range of Mie scattering. Normally the optical depth of these are modeled with a $\lambda^{-\alpha}$ scattering law (Angstrom 1929; Holben *et al*. 1998; Pakstiene, Zdanavicius and Bartasiute 2001), where α depends on the size distribution and refractive index of the particulate. Aerosol absorption is also not easily modeled. Under many circumstances there can be multiple types of aerosols present such that a single power law does not adequately describe optical depth (Pakstiene 2001).

  At most terrestrial sites the bulk of aerosols are contained in the boundary layer, below about 5 km above the surface, with a roughly exponential decrease of scale height between 0.5 km to 1.0 km. Aerosol layering within that altitude range is also common, especially for dust or smoke. The variability of boundary layer aerosols can be quite high, both spatially and temporally, though these two are linked as the aerosols blow over a given site. Aerosol opacity can also be sensitive to humidity. Depending upon the species of particles they can condense moisture on their surface and also swell as they absorb moisture, changing both their size distribution and index of refraction. Volcanic events can send aerosols into the stratosphere (up to 30 km), sometimes significantly affecting global atmospheric transmission over many months, though these events are rare and quite noticeable.

- Scattering by Clouds: In terms of atmospheric transmission, clouds are the limiting case of essentially no wavelength dependence but maximal spatial and temporal variations. The sizes of water droplets and ice crystals in clouds are typically large enough compared to optical wavelengths that scattering is 'gray' and has no wavelength dependence. It is clear from everyday observations that clouds are complex structures that vary

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with time and that move over a site with the prevailing winds. Thus, the variability of transmission and scattering due to clouds is complex and not easily modeled. The scale of angular variations in cloud transparency is small enough that calibrations of atmospheric transmission must be made along sensibly the same optical path through the atmosphere.

The effects of Earth's atmosphere are removed using the data ALE acquired about the molecular and aerosol absorption and scattering along the line of sight to the target. Water vapor and oxygen absorption bands are corrected using the PHOENIX Group stellar atmosphere model of the target star and MODTRAN model of the oxygen and water vapor telluric lines. The obtained spectrum itself will include enough information in the telluric lines to quantify the column depths for appropriate modeling. A high-level flowchart of this process is shown in Figure 8.

The AESoP telescope/spectrometer modified to include absolute flux and wavelength calibration will provide robust, accurate absolute calibration for stars with $V < 5$ at $S/N > 100$ per nanometer in one minute. The two largest sources of systematic errors in previous absolute calibration efforts are directly addressed by monitoring and modeling atmospheric transmission and calibration of AESoP to new, more accurate NIST standards. A long-term imaging photometric program to ensure the low-level photometric stability, supported by ALE and AESoP observations leads to a premier educational opportunity.

Note that in this process NIST, and other inter-compared international standard calibrators are the physical standards to which stars are calibrated. In a very real sense, because of the extremely long lifetimes of stars, maintenance of stars as radiometric standards depends upon the persistence of NIST and its counterpart institutions, and the continued observations of these stars both to ensure they are sufficiently constant and to incorporate (small) changes in the definition of radiometric standards and new calibration and comparison instrumentation.

4. HOW TO MONITOR EARTH'S ATMOSPHERE USING SI STARS

Having defined the problems inherent is establishing standard stars, and solved them, we can use the standard stars to monitor Earth's atmosphere on useful angular and temporal scales.

The model atmospheres and calibrated spectrophotometric observations of stars proven to be stable enough to be included in the catalog of SI Stars are legitimate source functions for measuring the wavelength-dependent transmission of Earth's nighttime atmosphere. A modification of the standardization procedure, shown in Figure 9, can now be instituted to provide fundamental data about the state of the atmosphere and conditions of radiative transport through it.

Atmospheric data derived from SI Stars can be directly compared with solar spectrophotometry and other daytime measurements obtained from existing distributed instruments to provide near-continuous day/night monitoring of the atmosphere. We propose that AESoP-derivative spectrophotometers will be sufficiently inexpensive to replicate and operate that many existing atmospheric and meteorological observatories will adopt nighttime spectrophotometric monitoring. Measurement of SI Stars to determine the wavelength-dependent transmission of the atmosphere is a valuable function for astronomical observatories worldwide, as well. We anticipate that approximately 50 observatories will regularly spectrophotometrically monitor SI Stars, with data used both for astronomical extinction corrections and in support of global monitoring.

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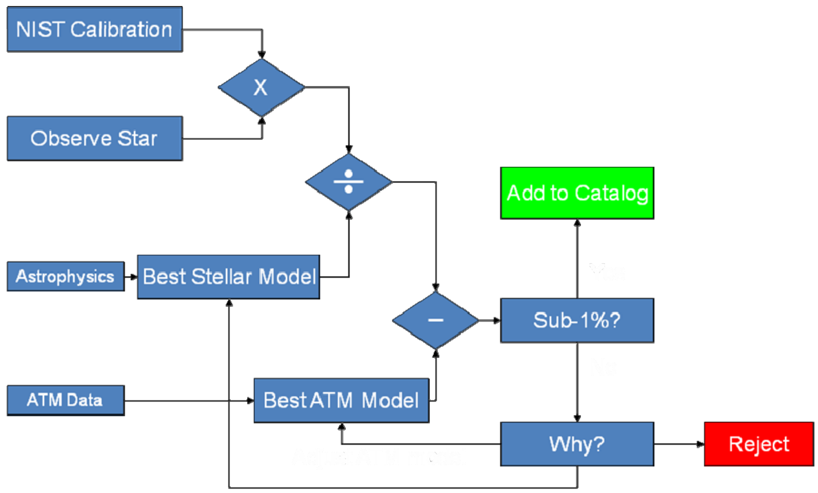

Figure 8. High-level flowchart of the procedure to create a spectrophotometric standard star. Iteratively fitting the "best" stellar model and the "best" atmospheric model allows refinement of the stellar model. After several nights of observing under different atmospheric conditions the stellar model stabilizes to acceptable levels and this star is vetted as a SI Stars member. It can be used in the future as a radiance standard for measuring the transmission of Earth's atmosphere and as a calibrator for ground- and space-based instruments.

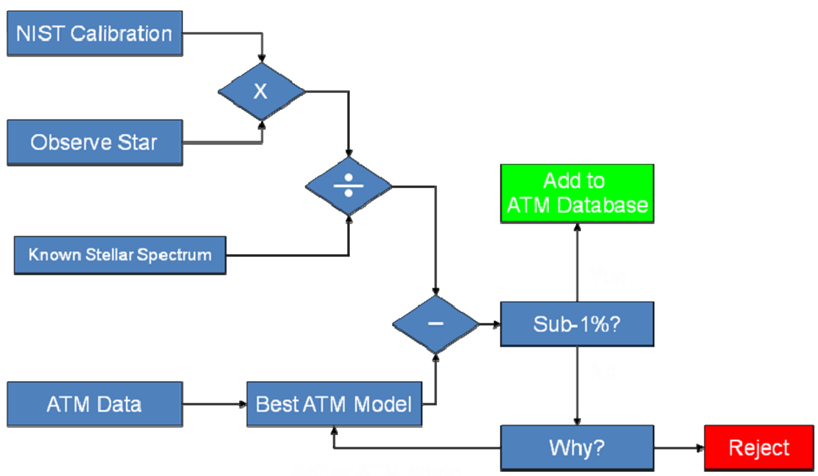

Figure 9. Flowchart leading to the best model of the atmosphere in the direction of SI Stars. The "best" model of Earth's atmosphere derived from comparing the measured stellar spectrum relative to the known stellar spectrum allows extraction of atmospheric parameters, including scattering and line absorption.

5. SUMMARY

The project described here shows the roadmap for using SI Stars as radiometric standards for climate change monitoring into the future. The Astronomical Extinction Spectrophotometer (AESoP), a spectrophotometer that will standardize primary standard stars, has been built and demonstrated. The Astronomical Lidar for Extinction (ALE), with AESoP, has the demonstrated capability to correct for the wavelength dependent transmission of Earth's atmosphere, the single greatest source of systematic error in calibrating stars as radiometric standards. We have reviewed the prior art of standardizing stars and have learned from these earlier efforts. NIST calibrated detectors and remote calibration

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instrumentation based on the NIST SIRCUS Facility provides a technique for field calibrating AESoP and other telescopes. We have described: 1. the end-to-end procedure for defining standard stars, and 2. the procedure to use these stars to monitor Earth's nighttime atmosphere. We have demonstrated that spectrophotometry is an information-rich technique of choice for observing Earth's atmosphere and for quantitatively measuring and monitoring climate change.

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REFERENCES

Angstrom, A. 1929 Geografiska Annaler, 11, 156

Berk, A., Anderson, G. P., Acharya, P. K., Bernstein, L. S., Muratov, L., Lee, J., Fox, M. J., Adler-Golden, S. M., Chetwynd, J. H., Hoke, M. L., Lockwood, R., Cooley, T., and Gardner, J. 2005, SPIE Conf. Series, 5655, 88

Brown, S.W., Eppeldauer, G.P., Rice, J.P., Zhang, J., and Lykke, K.R. 2004, Proc. SPIE **5542**, 363.

Bucholtz, A. 1995, Appl. Opt., 34, 2765.

Burrows, J. P., Richter, A., Dehn, A., Deters, B., Himmelmann, S., Voigt, S., and Orphal, J. 1999, J. Quant. Spectroscopy and Radiative Transfer, 61, 509.

Code, A. D. 1960, in Stars and Stellar Systems, Vol. 6, Stellar Atmospheres, ed. J. L. Greenstein (Chicago: University of Chicago Press), p. 50.

Dawsey, M., Gimmestad, G., Roberts, D., McGraw, J., Zimmer, P, and Fitch, J. 2006, SPIE Conf. Series, 6270, 47D.

Hale, G. E. and Wadsworth, F. L. O. 1896, Astrophysical Journal, **4**, 54.

Hansen, J. E. and Travis, L. D. 1974, Space Science Reviews, 16, 527.

Hayes, D. S. 1970, Ap. J. 159, 165.

Hayes, D. S. and Latham, D. W. 1975, Astrophysical Journal, 197, 593.

Hayes, D. S., Latham, D. W. and Hayes, S. H. 1975, Ap. J. **197**, 587.

Holben, B. N., Eck, T. F., Slutsker, I., Tanre, D., Buis, J. P., Setzer, A., Vermote, E., Reagan, J. A., Kaufman, Y. J., Nakajima, T., Lavenu, F., Jankowiak, I., Smirnov, A. 1998 Remote Sens. Environ., 66, 1.

IPCC 2007, *4th Assessment Rep.*, Pachauri, R. K. & Reisinger, A. (Eds.) http://www.ipcc.ch/ipccreports/ar4-syr.htm.

IPCC 2009, *IPCC Expert Meeting on the Science of Alternative Metrics*, Plattner, G-K., Stocker, T., Midgley, P. and Tignor, M. (Eds.) http://www.ipcc.ch/pdf/supporting-material/expert-meeting-metrics-oslo.pdf.

Larason, T. C. and Houston, J. M. 2008, NIST Special Publication 250-41, *Spectroradiometric Detector Measurements: Ultraviolet, Visible, and Near-Infrared Detectors for Spectral Power*.

Megessier, C. 1995, Astronomy and Astrophysics, 296, 771.

Oke, J. B. and Schild, R. E. 1970, Astrophysical Journal, 161, 1015.

Pakstiene, E. 2001, Baltic Astronomy, 10, 651.

Pakstiene, E., Zdanavicius, K., and Bartasiute, S. 2001, Baltic Astronomy, 10, 439.

Peterson, D. M., Hummel, C. A., Pauls, T. A., Armstrong, J. T., Benson, J. A., Gilbreath, G. C., Hindsley, R. B., Hutter, D. J., Johnston, K. J., Mozurkewich, D. and Schmitt, H. R. 2006, *Nature* **440**, 896.

Prather, K. A., Hatch, C. D. and Grassian, V. H. 2008, Ann. Rev. Analytic Chem. **1**, 485.

Smith, A. W., Woodward, J. T., Jenkins, C. A., Brown, S. W. and Lykke, K. R. 2009, Metrologia **46**, S219.

Sordo, R., Vallenari, A., Bouret, J.-C., Brott, I., Edvardsson, B., Frémat, Y., Heber, U., Josselin, E., Kochukhov, O., Korn, A., Lanzafame, A., Martins, F., Schweitzer, A., Thévenin, F., Zorec, J. 2009, MmSAI **80**, 103.

Stubbs, C. W. and Tonry, J. L. 2006, ApJ, **646**, 1436.

Stubbs, C. W., *et al.* 2007, Publ. Astron. Soc. of the Pacific, 119, 1163.

Tomasi, C., Vitale, V., Petkov, B., Lupi, A., and Cacciari, A. 2005, Appl. Opt., 44, 3320.

van Leeuwen, F. 2007, Astronomy and Astrophysics, **474**, Issue 2, 653.

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